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Performance Analysis of IEC 61850 Sampled Value Process Bus Networks

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***Abstract*—Process bus networks are the next stage in the evolution of substation design, bringing digital technology to the high voltage switchyard. Benefits of process buses include facilitating the use of Non-Conventional Instrument Transformers, improved disturbance recording and phasor measurement and the removal of costly, and potentially hazardous, copper cabling from substation switchyards and control rooms. This paper examines the role a process bus plays in an IEC 61850 based Substation Automation System. Measurements taken from a process bus substation are used to develop an understanding of the network characteristics of "whole of substation" process buses. The concept of "coherent transmission" is presented and the impact of this on Ethernet switches is examined. Experiments based on substation observations are used to investigate in detail the behavior of Ethernet switches with sampled value traffic. Test methods that can be used to assess the adequacy of a network are proposed, and examples of the application and interpretation of these tests are provided. Once sampled value frames are queued by an Ethernet switch the additional delay incurred by subsequent switches is minimal, and this allows their use in switchyards to further reduce communications cabling, without significantly impacting operation. The performance and reliability of a process bus network operating with close to the theoretical maximum number of digital sampling units (merging units or electronic instrument transformers) was investigated with networking equipment from several vendors, and has been demonstrated to be acceptable.**

***Index Terms*—Ethernet networks, IEC 61850, performance evaluation, process bus, power transmission, protective relaying, smart grids**

I. INTRODUCTION

THE "smart grid" is defined as an umbrella term for technologies that are an alternative to traditional practices in power systems, offering improved reliability, flexibility, efficiency and reduced environmental impact [1]. Much of the smart grid focus has been in electricity distribution, however there are many smart grid applications proposed for transmission substations. Improved disturbance recording and state estimation through phasor measurement is a goal of the transmission smart grid [2], and a networked process bus improves power network visibility by simplifying the connections required for advanced monitoring systems [3].

The high voltage equipment, including bus bars, circuit breakers, isolators, power transformers, current transformers (CTs) and voltage transformers (VTs), are the "primary plant" in a substation. The control equipment in a substation is termed the substation automation system (SAS), and includes protection, control, automation, monitoring and metering functions. The links between the primary plant and the SAS are called "process connections", and are typically copper wires conveying analog voltages and currents. A digital "process bus" carries information (such as indications, alarms and transduced analog data) from the primary plant to the SAS, and information (such as operating commands, configuration changes and status information of other plant) from the SAS to the primary plant, over a digital network. A standards-based interoperable process bus enables equipment from many vendors to operate together over a digital communications network.

There are many benefits of process buses, and these include simplified implementation of low impedance bus differential protection (one Ethernet cable can supply current data from all CTs in a substation, rather than requiring all CTs to be brought to the protection relay) [4], facilitation of Non-Conventional Instrument Transformers (NCITs) [5] and the elimination of potentially hazardous wiring from substation control rooms [6]. Utilities can reduce their field cabling, and hence construction costs, as one pair of optic fibers can take the place of 100 or more copper (wire) connections [7]. The use of data networks to replace point to point analog connections is not without risks. The cyber security requirements for industrial and real-time networks are quite different to those for business applications [8], [9].

Significant process bus product development is taking place, with equipment now available from various manufacturers and several process bus substations have been commissioned [10]. Despite this activity, little is known about the behavior of process bus networks, especially whole of substation process buses with a large number of data sources. The traffic characteristics are unknown (the content is known, but the timing characteristics are not), and this has been identified as an issue when dealing with other aspects of substation automation such as network based time synchronization using the Precision Time Protocol (PTP) [11]. Other research has identified the lack of "real world" data as an issue for meaningful research into future smart grid applications [12].

Communication networks are critical for smart grid appli-

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cations, and the benefits of a smart grid will not be realized if the performance of these networks is inadequate [13]. Much of the focus on smart grid communications is on distribution networks [14], [15] or synchrophasors [16], both of which cover wide area networks. The network traffic characteristics of a sampled value process bus local area network, with high data rates and strict performance requirements, are presented in this paper. These characteristics are based on measurements taken from a substation that uses a process bus for protection and control. The performance of a process bus with a large number of connected devices is verified experimentally in a laboratory environment.

Section II examines the details of sampled value communications and common implementations. Section III presents process bus performance results from substation testing. These results were used as the basis of laboratory based experimental testing of Ethernet switches, and the method and results are provided in Section IV. The paper concludes with Section V.

II. SAMPLED VALUE COMMUNICATIONS

The IEC Smart Grid standardization “roadmap” identifies the IEC 61850 series of standards as key components of substation automation and protection for the transmission smart grid. The objective of IEC 61850 is to provide a communication standard that meets existing needs of power utility automation, while supporting future developments as technology improves. Communication profiles that are part of IEC 61850 are based, where possible, on existing IEC/IEEE/ISO communication standards.

A. *IEC 61850 Models and Data Encoding*

The IEC 61850 series of standards are based on an object-oriented data model that is used to represent an automation system [17]. Functional decomposition introduces the concept of the “logical node” (LN), which is the smallest reusable part of a function that exchanges data. LNs are defined in detail in IEC 61850-7-4 [18]. Functions are implemented by one or more LNs, with communications links required between LNs that are implemented in physically separate devices. “Interfaces” are defined in [17] to link the *process*, *bay* and *station* levels of a substation. Information modeling defines the services, data objects, attributes that enable information to be readily exchanged. Interface IF4 is defined to be “CT and VT data exchange between process and bay levels”. Interface IF5 defines control data exchange between the process and bay levels. IF4 and IF5 together can be considered to be the process bus.

IEC 61850-7-2 defines the Abstract Communication Service Interface (ACSI). ACSI is independent of the underlying communications system and describes a means of client/server (connection based) and publisher/subscriber (connectionless) communications. Specific Communication Service Mappings (SCSMs) provide a concrete means of exchanging data in the physical world. The SCSM used for exchange of control and event information, IEC 61850-8-1, defines the Generic Object Oriented Substation Event (GOOSE) profile [19]. IEC 61850-9-2 defines an SCSM for the exchange of sampled values [20]. Existing standards have been used where possible in the development of the IEC 61850 family of standards. GOOSE and sampled values are based on IEEE Std 802.3/IEC 8802.3 Ethernet [21], with virtual LAN (VLAN) tagging based on IEEE 802.1Q used for prioritization [22]. Fast Ethernet using fiber optic connections (100BASE-FX) is preferred for its galvanic isolation and immunity to interference in high voltage switchyards.

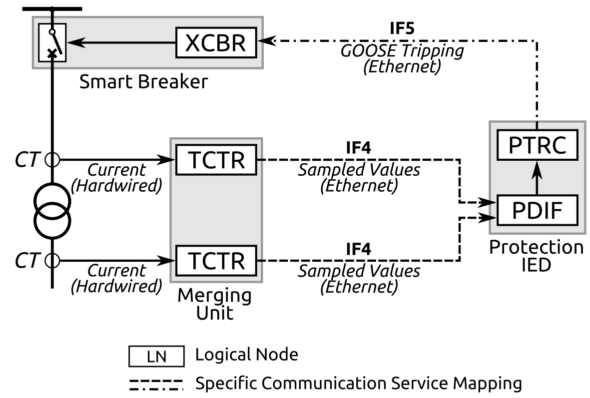

Fig. 1. Single line diagram of a digital process bus, including the primary plant and protection system..

Fig. 1 shows a high voltage power transformer connection (single-line format) with a circuit breaker, two CTs and a transformer. The protection function has been decomposed into the LNs TCTR (current transformer), PDIF (differential protection), PTRC (protection trip conditioning) and XCBR (circuit breaker). A “merging unit” is the generic name for a device that samples conventional CT and VT outputs. Non-Conventional Instrument Transformers (NCITs), such as electronic current transformers (ECTs) and optical current transformers (OCTs) usually publish sampled values directly from their secondary converters [23].

Fig. 1 shows the interfaces (IF4 and IF5) that provide communications between the process level LNs (TCTR, TVTR and XCBR) and the bay level LNs (PDIF and PTRC). TCTR, TVTR and XCBR (along with others) are single phase LNs, and three of each are required for a three phase system. Multiple protection LNs, such as PTOC (timed over-current) and PDIS (distance), are required for each zone (PDIS) or stage (PTOC). Multiple LNs of the same type are instantiated during system configuration.

B. *Common Implementations*

IEC 61850-9-2 specifies how sampled value measurements shall be transmitted over an Ethernet network by a merging unit or instrument transformer with electronic interface [20]. The UCAIug implementation guideline, referred to as “9-2 Light Edition” (9-2LE), reduces the complexity and difficulty of implementing an interoperable process bus based on IEC 61850-9-2 [24]. This is achieved by restricting the data sets that are transmitted and specifying the sampling rates, time synchronization requirements and the physical interfaces to be used. The 9-2LE dataset comprises four voltages and currents (three phases and neutral for each).

There is a considerable protocol overhead with IEC 61850-9-2 based sampled value transmission. A standard 802.1Q tagged Ethernet frame has twelve bytes of frame wrapping, twelve bytes of address information, four bytes of 802.1Q tag, two bytes of Ethertype and the payload. The sampled value payload defined in IEC 61850-9-2 has its own overhead with ASN.1 encoding and other fields that identify the source of the sampled data, and a time-stamp. Fig. 2 shows a 9-2LE frame for protection applications that is 126 bytes long, however only 32 bytes contain the sampled values (eight 32-bit integers). In the 9-2LE power quality application the Application Service Data Unit (ASDU) would be repeated a further seven times. In this case the *noADSU* attribute at offset 0x1E would be eight, and the ASDUs would be placed in a sequence to form the Protocol Data Unit (PDU).

It is suggested in [2] that moving from hard-coded transmissions to standards based protocols will improve efficiency, however this is not the case with sampled values. Interoperability comes at a cost, particularly in terms of data encoding efficiency. IEC 61850 based systems enable re-use of engineering designs, and therefore the engineering efficiency is increased through the use of standards.

C. Real-Time Data Networks

IEC 61850-5 specifies time limits for the delivery of messages, including GOOSE and sampled values [25]. The requirements for a message depend on the type of the message and the application performance class. Transmission substations (generally operating at 110-kV and above) require protection performance classes P2 ("normal") and P3 ("top performance"). Type 1A "Trip" messages for P2 and P3 applications must have a total transmission time below 3 ms, as do Type 4 raw data (sampled value) messages. This 3 ms includes the time required for handling the message by publishers (merging units or secondary converters) and subscribers (e.g. protection relays).

Sampled value traffic is continuous and the network load due to sampled values should not vary. GOOSE traffic is either periodic at a low rate ("heartbeat" messages), or sporadic at high rates (typically three messages sent over a few milliseconds). GOOSE messages on a process bus are expected to be commands from the SAS (e.g. switch open or close, circuit breaker trip or close, or transformer tap change controls), or status updates from the high voltage plant (e.g. digital indications, transduced analog values and command acknowledgments). High rate GOOSE traffic, such as that resulting from inter-tripping, should be restricted to the Station Bus network.

Event-based modeling tools have been used to model the behavior of sampled value networks [26], [27]. These models are only as accurate as the assumptions used to create them, and some have sampling rates and message sizes that do not reflect current implementations such as 9-2LE. Obtaining accurate models of hardened switches for substation applications can be prove difficult as there is much less demand for these devices than for switches with widespread commercial application.

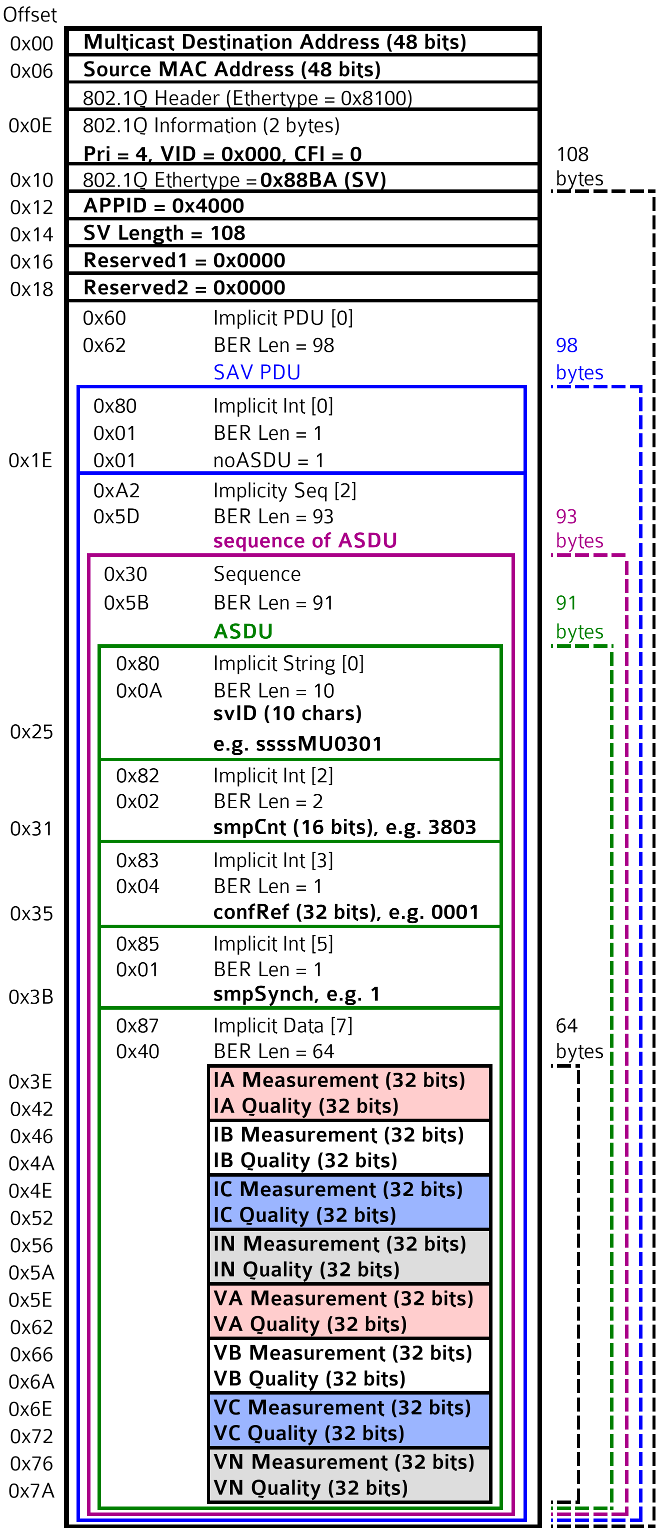

Fig. 2. Dissection of a 9-2LE sampled value frame, with key items shown in bold.

Network Calculus [28] and other analytic techniques have been used to predict network behavior when the load is variable [29]. The self-similarity of "normal" network traffic (its fractal nature) has been used in auto-regressive and wavelet traffic models [30], however such traffic is generally based on human activity. Sampled value networks by their nature have a near constant load. Occasional time-critical events occur in the reverse direction, such as circuit breaker operations, but the majority of the traffic is not influenced by human actions.

Management of traffic is important and this is often achieved through VLAN separation and multicast address filtering of the Ethernet frames [31]. Knowing the behavior of unrestricted traffic is helpful, and is presented in the following sections of this paper.

III. Substation Process Bus Testing

The time taken for a merging unit to sample the analogue waveform, or for an NCIT to derive its output value, was expected to be constant, as the required processing does not change from sample to sample.

Precision network analysis tools were taken to a 275-kV transmission substation and a series of packet captures were taken from the process bus networks. Data was collected from seven separate physical merging units. In this particular substation each merging unit operates in a "time island" and so latency measurements were taken separately.

A. Equipment used for Substation Test

An Endace DAG7.5G4 Ethernet capture card (DAG card) was used, as this card prepends a precise time-stamp to the captured frame [32]. The DAG card is capable of capturing or transmitting four 1000 Mb/s Ethernet streams (or a combination of capturing and transmitting), and includes a facility to synchronize its time-stamping clock to an external 1-PPS source. The time-stamping clock is integral to the Ethernet capture hardware, giving an absolute error of ±100 ns from the 1-PPS reference and a relative error of ±8 ns between the four capture ports. The time-stamp was used to measure the time taken for the current and voltage sample measured on the 1-PPS edge (where $smpCnt = 0$) to be transmitted by the merging unit [33].

The connections for these measurements are shown in Fig. 3. Testing was performed in a live substation, with the merging unit providing the 1-PPS reference over a fiber optic cable and the sampled values over 100BASE-FX Ethernet. The same fiber optic cables were used for all tests to ensure constant path delay. Each physical merging unit contained three logical merging units (each connected to a different set of three-phase current and voltage sensors) and an integrated Ethernet switch. The average inter-frame time of 3.6×10^6 frames between logical MU1 and logical MU2 was 41.5 µs (σ=0.72 µs), and between MU2 and MU3 was 42.0 µs (σ=0.73 µs).

The sampled value output of each merging unit was recorded for fifteen minutes, resulting in 900 frame arrival measurements (each relative to the 1-PPS synchronizing pulse). The merging units published 4000 frames per second and the inter-arrival time of each was measured, giving 3.6 million records per merging unit.

B. Merging Unit Results

The captured frames were filtered with the criterion $smpCnt = 0$. The "appearance delay" was then determined by taking the fractional second component of each frame's time-stamp. This gives the total time taken from the occurrence of the 1-PPS synchronizing signal to the appearance of the frame on the Ethernet. The appearance delays of all frames were averaged together to yield an overall mean appearance delay (which is commercially sensitive). The difference between this overall mean and each observation is termed the "offset from average". Sample distributions (histogram outlines) of the offset from average for the seven merging units are shown in Fig. 4. The frame appearance delays for the second and third logical MUs (not shown) are very similar. The test was repeated using an RTDS simulator with three merging unit cards (GTNET card with SV firmware). The results in Fig. 5 show that the three cards variable delays in publishing messages, but the three cards are consistent.

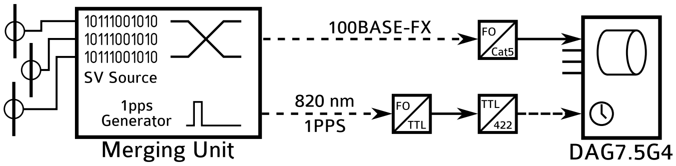

Fig. 3. Latency measurement using externally synchronized Ethernet capture card. FO/Cat5 is an Ethernet media converter, FO/TTL is a 1-PPS fiber optic receiver, and TTL/422 is a voltage level converter for the DAG card.

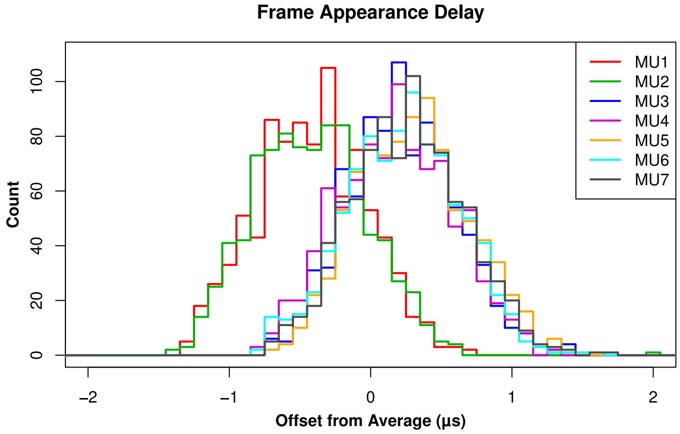

Fig. 4. Sample distributions (histogram outlines) for variation in frame arrival time for the first logical merging unit in each of seven physical merging units. Each curve is calculated from 900 1-PPS samples.

The total variation is from –1.5 µs to 2.0 µs, and confirms that this model of merging unit had processing times that were very similar, validating the hypothesis on constant delay. The mean delay of merging units 1 and 2 differs from merging units 3–7 by 0.65 µs, however the spread is similar for all merging units (the sample standard deviation is 0.38 µs). This confirms that if all merging units are synchronized from the same source the frames transmitted from the same model of merging unit will arrive at the Ethernet switch at the same time. There will be some variation due to path length, and for cabling up to 1000 m in length this would not exceed 5 µs (less than half the transmission time of a sampled value frame at 100 Mb/s).

All captured frames were used in the analysis of inter-frame arrival time. This is a measure of the regularity of

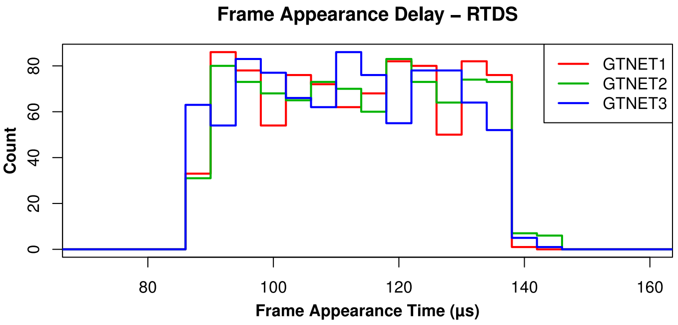

Fig. 5. Sample distributions (histogram outlines) for variation in frame arrival time for GTNET sampled value publishers in an RTDS simulator. Each curve is calculated from 900 1-PPS samples.

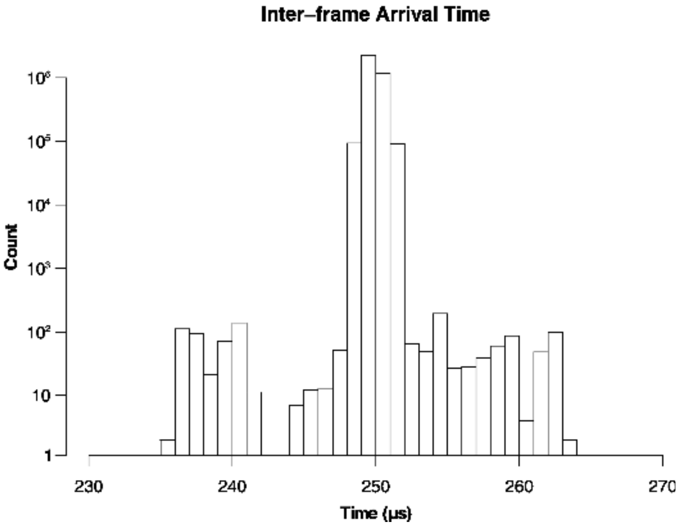

Fig. 6. Histogram showing the frame inter-arrival times for Merging Unit 1, with a logarithmic y-axis. $n = 3.6 \times 10^6$.

frame transmission by the merging unit. The histogram in Fig. 6 shows that the majority (99.97%) of frames are spaced between 248 µs and 252 µs, with inter-arrival times bounded by 235 µs and 264 µs. This confirms that the data transmission is regular. The inter-arrival time distributions of merging units 2–7 were calculated, and the intervals for each found to have the same characteristic as merging unit 1.

The combination of frame transmission occurring at the same point in time (*synchronization*) and at the same rate (*syntonization*) means that the merging unit transmissions can be considered *coherent transmissions*, using terminology analogous to that of coherent light (light that has the same wavelength and phase).

This test was conducted with merging units from one manufacturer, however these results show that coherent transmission is possible with commercially available merging units, and this is the worst case as the results will show. As a result, network designers need to allow for the simultaneous arrival of frames when specifying Ethernet switches.

IV. LABORATORY INVESTIGATION OF ETHERNET SWITCHING BEHAVIOR

The handling of sampled value data by Ethernet switches is of interest to network designers, and is an important part of undertaking a detailed process bus network design. The approach taken was to inject synthetic sampled value data into various Ethernet switches and then observe how the frames were handled. This laboratory based testing reproduces the substation environment described in Section III, but in a controlled and repeatable manner.

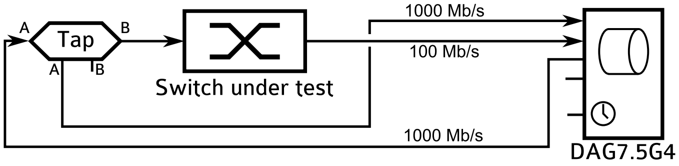

Fig. 7. Configuration used for the measurement of sampled value frame latency.

The synthetic data was based upon standard 9-2LE frames and was created with a custom application that allows key parameters to be varied. Synthetic data avoids the reproduction of variations in inter-frame time that may occur with a real merging unit, and this provided consistency between tests.

The test frames were injected into switches under test via a full-duplex Ethernet tap (NetOptics 10/100/1000 Tap), as shown in Fig. 7. The tap output was captured with the DAG card, providing accurate switch ingress time-stamps. A second capture port on the DAG card captured the frames leaving the switch, and from this the residence time, or latency, was calculated. The DAG card used a common clock to time-stamp all frames entering the card, and the resolution of this clock was 7.5 ns.

A. Six Sampled Value Streams

Fig. 8 shows an application where six merging units connect to a single Ethernet switch, and is based upon a "breaker and a half" substation with overlapping protection (refer to Section 11 of [34] for more detail on substation layouts). This Ethernet switch would reduce the amount of cabling from the switchyard to the control room.

Network traffic was created for the switches under test that reflected this environment. Six synthetic sampled value "streams" were created, with each merging unit offset from the previous merging unit by a fixed time to ensure consistency when switching. The synthetic data was injected into the switch under test at 1000 Mb/s to simulate the near simultaneous arrival of frames from six merging units.

The spacing of frame arrivals has a significant effect on the latency that is introduced. Fig. 9(a) shows the cumulative probability of latency for two configurations. The "bunched" case has the messages from the six merging units arriving at 2 µs intervals, while the "spaced" data arrives at 42 µs intervals (the 250 µs sampling period divided by six). The output queuing experienced by the bunched data is apparent, with the last frame of the bunch having an additional 55 µs latency. The spaced merging unit transmissions all experience the same latency as there is no queuing.

Once the bunched frames have passed through one switch they are serialized, and as a consequence pass through subsequent switches with minimum additional latency. Fig. 9(b)

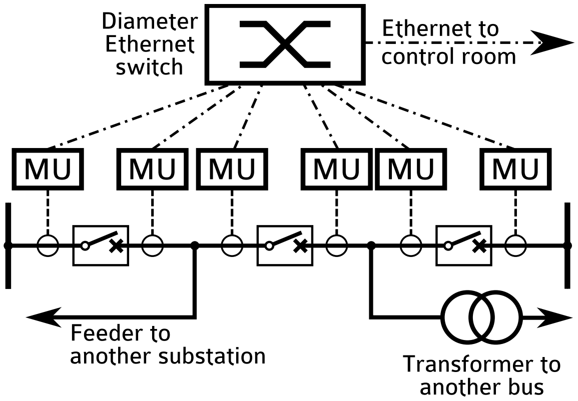

Fig. 8. Schematic of an application where six logical merging units connect to one Ethernet switch.

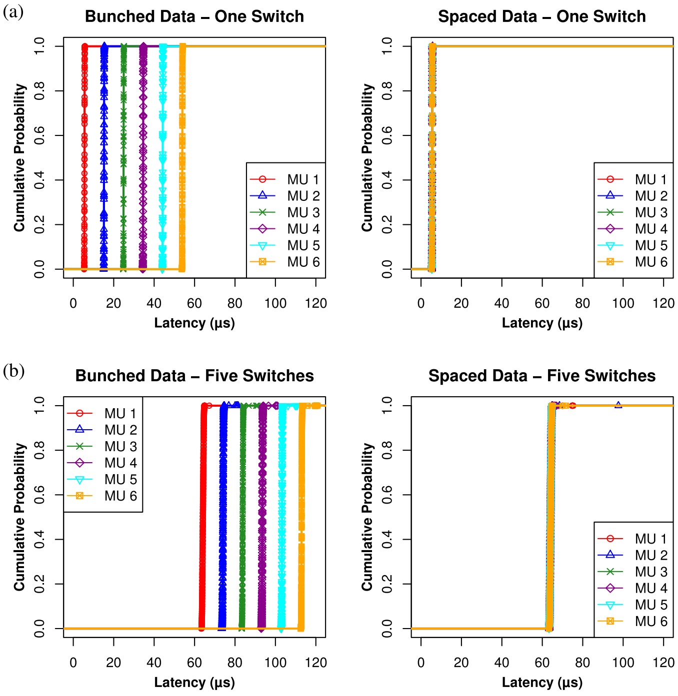

Fig. 9. Six sampled value streams, showing effect of frame spacing and number of switches, with (a) one switch and (b) five switches.

shows observed latency for bunched and spaced sampled value frames that have passed through five Ethernet switches in series (with no additional traffic introduced). This is a significant result as a fixed 15 μs latency, rather than load dependent latency (of up to 250 μs), is introduced by each switch.

B. Limits of Capacity

The maximum latency when there is no packet loss is expected to be 250 μs, as this is the sampling period (50 Hz and 80 samples per cycle). The theoretical limit on the number of merging units is 22 (97.2 Mb/s) with a 50 Hz power system and 126 byte sampled value frames. Synthetic sampled value transmissions were made with 21, 22 and 23 merging units to test this. The transmissions from the DAG card to each switch were at 1000 Mb/s. The frames were spaced at 2 μs intervals to simulate the near simultaneous arrival of frames from a number of merging units. Each sampled value frame was VLAN tagged and had a priority of 4. The buffer memory in the DAG card limited transmissions to 7 s. The frame spacing was found to be bi-modal with values of 249.86 μs (42%) and 250.10 μs (58%), confirming that the DAG card transmitted the frames at the correct rate, and that 2 μs frame spacing was sufficient.

Three makes of substation rated managed Ethernet switches with PTP transparent clock functionality were tested (Cisco, Hirschmann and RuggedCom), and these were identified as switches A, B and C (in no particular order). No rate limiting or policing was used and the switches were not loaded with any other traffic. Switch management links were disconnected for the duration of each test.

Incoming and outgoing frames were counted for each merging unit in the stream. Table I summarizes the results for each combination of network load (21, 22 or 23 merging units) and Ethernet switch (A, B and C). The transmissions with 21 merging units experienced no frame loss with any of the switches. Frame loss did occur with the 22 and 23 merging unit streams, and mainly affected the 22nd and 23rd merging units in the sequence, while merging units 19, 20 and 21 lost a few frames. The frame loss rate is almost identical across the three makes of switch, and this suggests that this behavior is not due to any particular switch implementation.

The latency for each merging unit was determined by calculating the difference between the egress and ingress time-stamps of each frame, which is also called the “switch residence time”. The network tap was used to feed the transmitted synthetic SV data back into the DAG card, ensuring the ingress and egress time-stamps were consistent. This compensates for any delays in transmitting the SV messages by the DAG card.

The switches are able to service the load of 21 merging units, and latency remains relatively constant for each merging unit. Fig. 10 shows the variation in latency for each merging unit over a 7 s interval. MU1 is colored red, and has the smallest latency, while MU21 is colored magenta and has largest latency. Small changes in latency occur periodically as the switches take a little longer to process some frames, and these show as “blips”. This may be due to spanning tree and PTP peer delay messages that are generated by the switch entering the output queue. The load from 21 merging units is low enough that the switches were able to recover from this incidental traffic without dropping frames due to buffer overflow. No collisions occur as the full duplex links and Ethernet switches are used. The effect of switching is to incur latency through buffering, and if the buffers overflow then frames are lost.

Fig. 11 shows the start of transmission for the 22 and 23 merging unit streams, and it can be seen that there are frames missing with 23 merging units (each frame from MU22 or MU23 is shown with a marker). This is an indicator that these Ethernet switches cannot serve the network load presented by 22 or 23 merging units.

The maximum latency does vary between the switches that were tested, and frames are dropped sooner by the switch with the lower maximum latency. Table I shows slightly higher

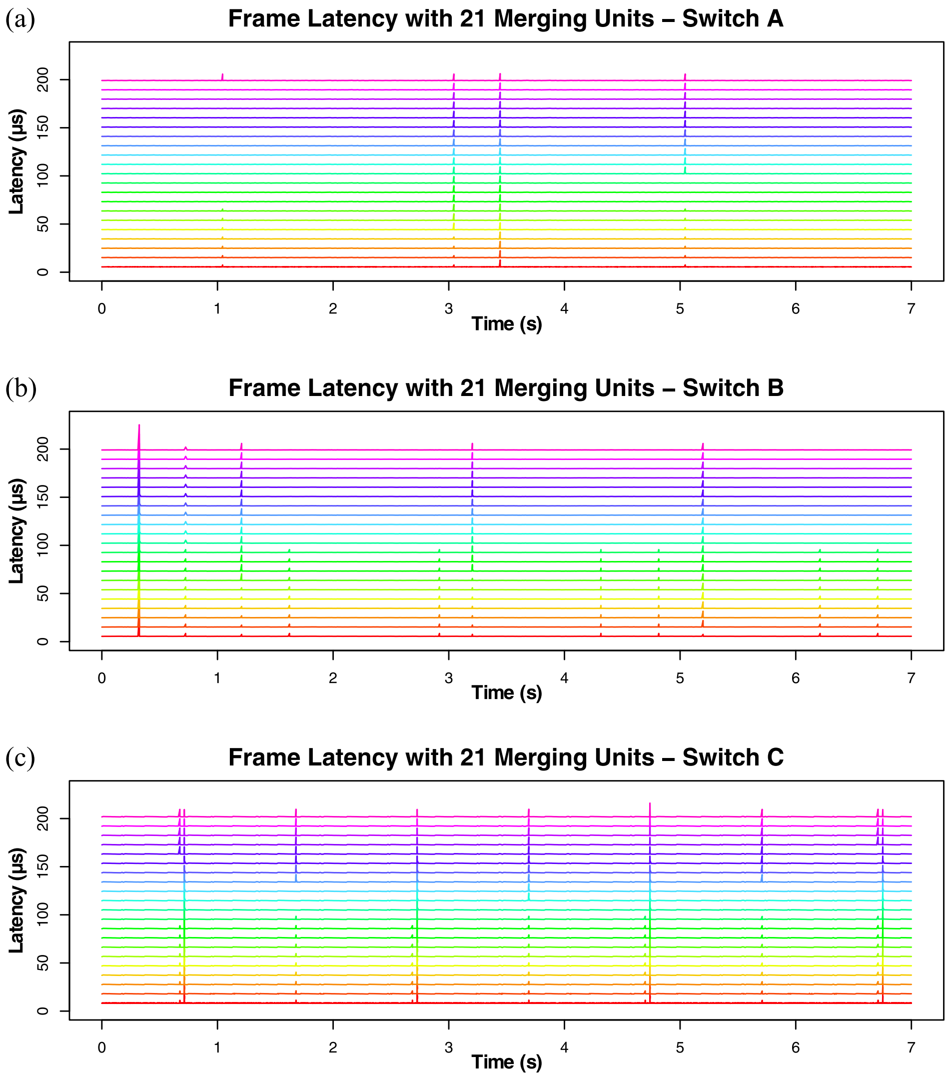

Fig. 10. Time series of observed latency for each of the 21 merging units, tested with three Ethernet switches. Each merging unit is shown in a different color, ranging from red (MU1, smallest latency) to magenta (MU21, greatest latency).

frame loss for switch C than for switches A or B.

This test can be used for system design or factory acceptance testing to verify that the data network performs to specification with the expected number of merging units. The safe operating margin can be determined by increasing network load until latency no longer remains constant.

An additional test was conducted with five Ethernet switches in series. No frames were dropped with 21 merging units and the results for 22 and 23 merging units were similar to the single switch cases. This was expected, since the first switch drops frames to limit the outgoing connection to 100 Mb/s, and each subsequent switch can accommodate this rate.

V. CONCLUSIONS

This paper has examined the application of process bus networks based on IEC 61850, and how Specific Communication Service Mappings are used to provide information flow between the logical nodes that form the automation system. Unique characteristics of sampled value networks, which have hard real-time requirements, have been presented. Measurements from a live substation have confirmed that transmissions from merging units can occur at the same time and at the same rate, and the term *coherent transmission* has been introduced to describe this type of data. This data is machine derived, unlike more traditional self-similar data that is generated in response to human activity.

Coherent transmission from merging units affects the switching performance of Ethernet switches, with additional latency introduced due to output queuing delays. Once the frames are queued subsequent Ethernet switches introduce minimal delay, which is determined by the size of the frame. This permits the use of Ethernet switches in the field to reduce cabling from the switchyard to the control room of a substation, without significantly impacting network performance.

Sampled value networks operating close to theoretical capacity limits have been demonstrated in a controlled test environment that replicated a process bus substation. A test methodology has been developed that identifies when network capacity is reached and can be used to assess the safe limits of operation for a data network. This testing used a precision

MU	Frames Sent	Frames Lost								
		21MU			22MU			23MU		
		Sw. A	Sw. B	Sw. C	Sw. A	Sw. B	Sw. C	Sw. A	Sw. B	Sw. C
1–18	28 000	0	0	0	0	0	0	0	0	0
19	28 000	0	0	0	0	0	0	0	1	1
20	28 000	0	0	0	0	0	0	0	0	2
21	28 000	0	0	0	1	6	5	4	7	8
22	28 000	—	—	—	16 520	16 526	16 537	21 377	21 407	21 406
23	28 000	—	—	—	—	—	—	23 141	23 118	23 128
Overall Loss		0.00%	0.00%	0.00%	2.68%	2.68%	2.69%	6.91%	6.92%	6.92%

TABLE I
FRAMES LOST AT HIGH NETWORK LOADS WITH THREE MAKES OF ETHERNET SWITCH, BY MERGING UNIT POSITION IN THE STREAM.

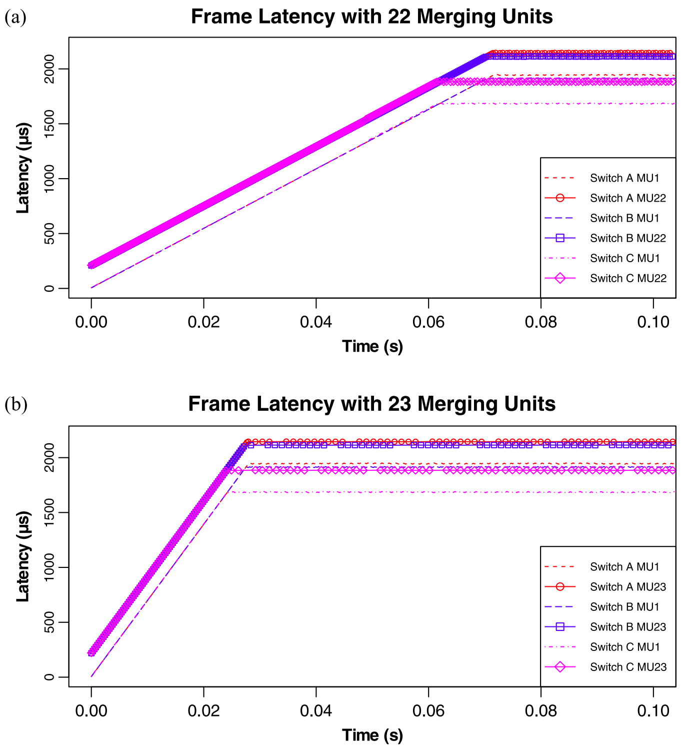

Fig. 11. Start of transmission with (a) 22 and (b) 23 merging units, showing increasing latency and dropped frames when latency reaches a limit.

Ethernet capture card and commercially available Ethernet switches, and is therefore more representative of the substation environment than event-based simulation models.

Process bus networks have been shown to be reliable, even at very high network loads. This provides confidence that the "whole of substation" process bus is viable, and that centralized applications such as disturbance recording, phasor measurement and even protection are feasible. Process buses will also facilitate the adoption of NCIT technology in transmission substations, resulting in a safer work environment and reduced environment impact.

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REFERENCES

[1] V. Hamidi, K. S. Smith, and R. C. Wilson, "Smart grid technology review within the transmission and distribution sector," in *Proc. Innov. Smart Grid Tech. Conf. Europe 2010 (ISGTE)*, Gothenburg, Sweden, 11–13 Oct. 2010.

[2] D. E. Bakken, A. Bose, C. H. Hauser, D. E. Whitehead, and G. C. Zweigle, "Smart generation and transmission with coherent, real-time data," *Proc. IEEE*, vol. 99, no. 6, pp. 928–951, Jun. 2011.

[3] Fangxing Li, Wei Qiao, Hongbin Sun, Hui Wan, Jianhui Wang, Yan Xia, Zhao Xu, and Pei Zhang, "Smart transmission grid: Vision and framework," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 168–177, 2010.

[4] M. Zadeh, T. Sidhu, and A. Klimek, "Suitability analysis of practical directional algorithms for use in directional comparison bus protection based on IEC61850 process bus," *IET Gener. Transm. Distrib.*, vol. 5, no. 2, pp. 199–208, Feb. 2011.

[5] P. Schaub, J. Haywood, D. M. E. Ingram, A. Kenwrick, and G. Dusha, "Test and evaluation of Non Conventional Instrument Transformers and sampled value process bus on Powerlink's transmission network," in *CIGRE Sth East Asia Prot. Autom. Conf. 2011 (SEAPAC)*, Sydney, Australia, 10–11 Mar. 2011.

[6] D. McGinn, M. G. Adamiak, M. Goraj, and J. Cardenas, "Reducing conventional copper signaling in high voltage substations with IEC 61850 process bus system," in *Proc. 2009 IEEE Bucharest PowerTech*, Bucharest, Romania, 28 Jun. – 2 Jul. 2009.

[7] D. M. E. Ingram, D. A. Campbell, P. Schaub, and G. Ledwich, "Test and evaluation system for multi-protocol sampled value protection schemes," in *Proc. 2011 IEEE Trondheim PowerTech*, Trondheim, Norway, 19–23 Jun. 2011.

[8] D. Wei, Y. Lu, M. Jafari, P. Skare, and K. Rohde, "Protecting smart grid automation systems against cyberattacks," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 782–795, Dec. 2011.

[9] M. Cheminod, L. Durante, and A. Valenzano, "Review of security issues in industrial networks," *IEEE Trans. Ind. Informat.*, vol. PP, no. 99, pp. 1–17, 2012. [Online]. Available: `http://dx.doi.org/10.1109/TII.2012.2198666`

[10] R. Moore and M. Goraj, "New paradigm of smart transmission substation - practical experience with Ethernet based fiber optic switchyard at 500 kilovolts," in *Proc. 2nd IEEE PES Int. Conf. Exhib. Innov. Smart Grid Tech. Europe (ISGTE)*, Manchester, UK, 5–7 Dec. 2011, pp. 1–5.

[11] J. Amelot, Y.-S. Li-Baboud, C. Vasseur, J. Fletcher, D. Anand, and J. Moyne, "An IEEE 1588 performance testing dashboard for power industry requirements," in *Proc. 2011 IEEE Int. Symp. Precis. Clock Synchr. Meas. Control Commun. (ISPCS)*, Munich, Germany, 12–16 Sep. 2011, pp. 132–137.

[12] L. Vanfretti, D. Van Hertem, L. Nordström, and J. O. Gjerde, "A smart transmission grid for europe: Research challenges in developing grid enabling technologies," in *IEEE PES Gen. Meet. 2011*, Detroit, MI, USA, 26–28 Jul. 2011.

[13] Q. Yang, J. A. Barria, and T. C. Green, "Communication infrastructures for distributed control of power distribution networks," *IEEE Trans. Ind. Informat.*, vol. 7, no. 2, pp. 316–327, May 2011.

[14] T. Sauter and M. Lobashov, "End-to-end communication architecture for smart grids," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1218–1228, Apr. 2011.

[15] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. Hancke, "A survey on smart grid potential applications and communication requirements," *IEEE Trans. Ind. Informat.*, vol. PP, no. 99, pp. 1–14, 2012. [Online]. Available: `http://dx.doi.org/10.1109/TII.2012.2218253`

[16] P. Kansal and A. Bose, "Bandwidth and latency requirements for smart transmission grid applications," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1344–1352, Sep. 2012.

[17] *Communication Networks and Systems in Substations – Part 1: Introduction and Overview*, IEC TR 61850-1:2003(E), Apr. 2003.

[18] *Communication Networks and Systems for power utility automation – Part 7-4: Basic information and communications structure – Compatible logical node classes and data object classes*, IEC 61850-7-4 ed2.0, Mar. 2010.

[19] *Communication networks and systems for power utility automation – Part 8-1: Specific communication service mapping (SCSM) – Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3*, IEC 61850-8-1 ed2.0, Jun. 2011.

[20] *Communication networks and systems for power utility automation – Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3*, IEC 61850-9-2 ed2.0, Sep. 2011.

[21] *IEEE Standard for Local and Metropolitan Area Networks – Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications*, IEEE Std. 802.3-2008, 26 Dec. 2008.

[22] *IEEE Standard for Local and Metropolitan Area Networks – Media Access Control (MAC) Bridges and Virtual Bridge Local Area Networks*, IEEE Std. 802.1Q-2011, 31 Aug. 2011.

[23] D. Chatrefou, "Process bus application in NCIT experiments; impact on future architectures," in *Proc. 17th Conf. Elec. Pwr Sup. Ind. (CEPSI)*, Macau, China, 27–31 Oct. 2008.

[24] UCA International Users Group. (2004, 7 Jul.) Implementation guideline for digital interface to instrument transformers using IEC 61850-9-2 R2-1. Raleigh, NC, USA. [Online]. Available: `http://iec61850.ucaiug.org/Implementation%20Guidelines/DigIF_spec_9-2LE_R2-1_040707-CB.pdf`

[25] *Communication Networks and Systems in Substations – Part 5: Communication Requirements for Functions and Device Models*, IEC 61850-5:2003(E), Jul. 2003.

[26] M. S. Thomas and I. Ali, "Reliable, fast, and deterministic substation communication network architecture and its performance simulation," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2364–2370, 2010.

[27] M. G. Kanabar and T. S. Sidhu, "Performance of IEC 61850-9-2 process bus and corrective measure for digital relaying," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 725–735, Apr. 2011.

[28] R. L. Cruz, "A calculus for network delay, part i: Network elements in isolation," *IEEE Trans. Inf. Theory*, vol. 37, no. 1, pp. 114–131, 1991.

[29] K. Schmidt and E. G. Schmidt, "A longest-path problem for evaluating the worst-case packet delay of switched ethernet," in *Proc. 5th IEEE Symp. Ind. Embed. Syst. (SIES)*, Trento, Italy, 7–9 Jul. 2010, pp. 205–208.

[30] J. Kolbusz, S. Paszczyński, and B. M. Wilamowski, "Network traffic model for industrial environment," *IEEE Trans. Ind. Informat.*, vol. 2, no. 4, pp. 213–220, Nov. 2006.

[31] D. M. E. Ingram, P. Schaub, and D. Campbell, "Multicast traffic filtering for sampled value process bus networks," in *Proc. 37th Ann. Conf. IEEE Indust. Electron. Soc. (IECON)*, Melbourne, Australia, 7–10 Nov. 2011, pp. 4710–4715.

[32] J. Micheel, S. Donnelly, and I. Graham, "Precision timestamping of network packets," in *Proc. 1st ACM SIGCOMM Wkshp Internet Meas.*, San Francisco, CA, USA, 1–2 Nov. 2001, pp. 273–277.

[33] D. M. E. Ingram, F. Steinhauser, C. Marinescu, R. R. Taylor, P. Schaub, and D. A. Campbell, "Direct evaluation of IEC 61850-9-2 process bus network performance," *IEEE Trans. Smart Grid*, vol. PP, no. 99, pp. 1–2, 2012. [Online]. Available: `http://dx.doi.org/10.1109/TSG.2012.2205637`

[34] H. Gremmel, *Switchgear Manual*, 11th ed. Berlin, Germany: ABB / Cornelsen Verlag Scriptor GmbH & Co. KG, 2006. [Online]. Available: `http://www.abb-shb.de/content.asp?lang=en`

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